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Buckling of composite domes with localised imperfections and subjected to external pressure

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ABSTRACT

It is shown that Force-Induced-Dimple (FID), initial geometric imperfection leads to a far worse deterioration of buckling strength (for up to four times) than currently used modulated eigenshape(s) or lower bound increased-radius shape deviations from perfect geometry. The FID approach provides not only safer estimates of buckling resistance but also it is efficient in terms of computing time for a range of shell geometries. The physics behind the FID-concept is closer to reality than in the other two approaches.

1. Introduction

Externally pressurised doubly curved shells can be found in aerospace and underwater applications, and among others, they include spherical caps, hemispheres, ellipsoids and torispheres which usually serve as domed closures onto cylinders. Their load carrying capacity, when subjected to external pressure, can be affected by static stability loss (bifurcation, collapse, snap-through), and this is one of fundamental design limitations. Ref. [1], apart from static stability addresses also the issue of initial geometric imperfections for the above shells. But it deals primarily with isotropic shells and there is little information both theoretical and experimental on composite, doubly curved shells subjected to external pressure. Large number of research output has appeared since the publication of the report, e.g., Refs [2–5]. Substantial theoretical and experimental programme into strength, static buckling and collapse of externally pressurised FRP domes is reported in Refs [6–8]. Shells of approximately 200 mm and 1000 mm diameter were manufactured from woven cloth as well as from unidirectional fibres – both dry and pre-preg. The algorithm describing the fibre trajectories in different draping scenario were developed and benchmarked against the experimental data, Ref. [9]. Winding patterns for dry and wet (pre-preg) fibres were also investigated, Ref. [10]. Analyses included search for First Ply Failure, progressive failure for up to the Last-Ply-Failure, bifurcation and collapse loads. The up-to-date list of references related to strength and/or buckling of spheroidal shells, as well as, of other geometries can be found in Refs [11,12]. Various other aspects of buckling phenomena in shells of double curvature are comprehensively covered in the web resource, Ref. [13].

As mentioned earlier, imperfection sensitivity of buckling pressure for composite shells was not addressed in the report, Ref. [1], at all but the subject has gained importance due to perceived use of composite shells both as primary and secondary structures in aerospace as well as in their use in underwater structures. Buckling of geometrically imperfect shells has been a subject of major research effort for many of recent decades once it had been discovered that initial geometric imperfections are behind the large discrepancy between experiment and theory. In order to ascertain sensitivity of buckling load to initial deviations from perfect shape one has to decide what are these shape deviations, i.e., how they are defined, where they are positioned, what their maximum amplitude is, etc. These questions still remain open ones. Over the years a number of approaches to modelling shape of initial geometric imperfections have been tried. The shape which reduces the buckling strength the most has always been sought as this would allow the designer to plan for the worst possible scenario, Ref. [14].

The imperfections in fabricated domes are likely to be distributed randomly and will normally consist of dimples and increased-radius flat spots of various sizes. Here one can mention the following three non-aerospace design recommendations, PD 5500 – Ref. [15], ASME – Ref. [16], ECCS – Ref. [17]. Ref. [16] provides recommendations on design practices of comprehensively loaded doubly curved shells, including spheroids in addition to torispheres and toroids with open and closed cross-sections. In

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Ref. [15] recommendations for hemispherical and oblate ellipsoidal heads are given. The latter code covers metallic heads, only.

There appears to be limited amount of knowledge on buckling performance of imperfect vessel end closures made from composites (unlike for the case of composite cylindrical shells, e.g., Ref. [18]). The concept of Force-Induced-Dimple has recently been advocated for composite cylinders under axial compression, and there is some experimental back-up/benchmarking available ($D/t \approx 500$, $L/R \approx 2.0$), Ref. [18]. It has been recently shown that for metallic heads the Force-Induced-Dimple (FID) in doubly curved shells, has a number of advantages over the lower bound concept which otherwise has been successfully used for two decades or so, Ref. [19]. These include much faster computing of sensitivity response and being able to trace physics in the case of compound shells, e.g., in torispherical heads. In the latter case it has been found that small amplitude shape deviations do not dissipate the buckling strength. This explicitly contradicts an entrenched belief in the eigenmode modelisation of imperfections as leading to the worst buckling performance scenario. If shape imperfections occur in the transition region of spherical cap – knuckle region then the eigenmode approach is correct. But this is not applicable to the rest of shell's surface. The FID modelling, on the other hand, is able to capture the sensitivity both away from the transition region as well as at it.

Questions have always been raised about how realistic are deviations from perfect geometry in the form of eigenmode(s) especially when taken as a string of regular in-out-deformations. It has been shown in Ref. [14], for example, that if one extracts one halve wave from the eigenshape as the new shape imperfection then the sensitivity of buckling pressure literally follows the same response as for the whole eigenshape imperfection pattern. This obviously does not answer the question what will happen when this 'single eigen-dimple' is positioned elsewhere at shell's surface. An answer to this is the creation of a localised dimple by a concentrated force which is much simple to create and easier to move around. Also, occurrence of such localised inward dimple is more likely to be seen in practice than that of 'eigen-dimple'. As mentioned above, the inward dimples created by a concentrated force, in metallic shells, can lower the buckling strength well below the other commonly used imperfection patterns. But the response of composite domes to this pattern of imperfection remains unknown.

The current paper discusses the intricateness of the above modelling of initial shape imperfections as applied to multi-ply composite domes under static external pressure. This is entirely numerical study based on the FE approach. Material used is CFRP in epoxy resin with standard properties. Geometries considered include hemispherical, ellipsoidal and torispherical.

2. Composite domes

2.1. Background

Domed closures onto cylindrical shells have been used across the range of industries. Hence they are found in a wide spectrum of applications and loading conditions. One of them is related to external pressure (or vacuum). They were considered for new breed of space launchers (common bulkhead separating LOX and LH_2) and for underwater activities. The latter is spanning different submersibles and buoyancy units – Fig. 1. Medium to deep-sea exploration of ocean floors would require a range of buoyancy solutions. Syntactic foam developed recently has been applied in sea bed exploration of natural resources. It also allowed a fresh dive to the full depth of the ocean (11 km, Ref. [20]). But buoyancy units, usually referred to as pressure hulls, are still a subject of research. What appears to be the first fully composite submarine was developed in seventeens of the last centenary with the operational depth within 200 m and 400 m, Ref. [21]. Further research in this area has continued, among others, in multinational European program MAST I&II where it was assumed that the hull will have a cylinder capped by two domes. There are two obvious ways of manufacturing composite dome closures worth mentioning, i.e., by filament winding and by draping woven cloth.

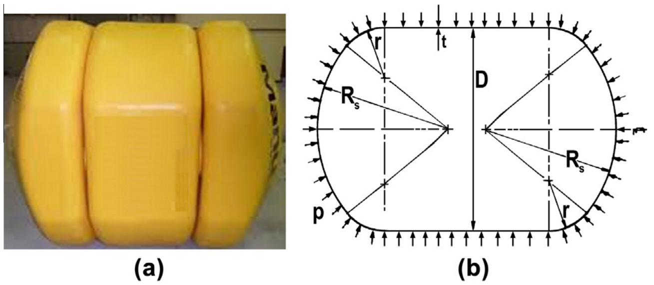

Fig. 1. Buoyancy unit assembled from blocks of syntactic foam (a), and buoyancy unit of a vessel type (b).

Polar filament winding has been primarily used for winding vessels to carry internally pressurised media. But as seen in Fig. 2 the method can also be used to manufacture shells aimed at external pressure. 'Straight forward' polar winding, seen in Fig. 2a produces a dome (torispherical in this case, Fig. 2c) with an apex hole, and substantial accumulation of wall thickness. But as shown in Ref. [22] the latter can be appropriately redistributed by adjusting the cover sequencing and the inclination angle of the shaft. The second approach (Fig. 2b) produces a dome without the apex hole – as seen in Fig. 2d. The shell is axisymmetric geometrically, but its material properties are not. Hence the structural analysis would require in this case full 2D modelling. A different approach to manufacturing composite dome is based on draping woven material into either female or male moulding tool. CFRP dome shown in Fig. 3a is just such a case. Again, geometry is axisymmetric here but the material properties are not. This is best seen by comparing Fig. 3a and b where the trajectories of woven fabric are distinctly different. Each ply will therefore require the application of draping algorithm predicting local fibre orientation and local wall thickness and these quantities to be transferred to the FE model – as illustrated in Fig. 3c. Further details into the above can be found in Refs [6–10].

2.2. Preliminaries, modelling and analysis details

In the current study, the wall of a shell is to be made from N plies stacked at angles $\theta_1, \ldots, \theta_N$ with respect to the meridian – see Fig. 4c. Ply number '1' is the innermost ply whilst ply no. 'N' is the most outer one. The stacking sequence may not necessarily be symmetric with respect to the mid-surface. Classical lamination theory is to be adopted in all of the ensuing analyses. In the current study, the bifurcation buckling pressure, the collapse pressures, and First Ply Failure (FPF) are to be found numerically using BOSOR4, Ref. [23] and ABAQUS, Ref. [24]. Bosor4 performs stress, buckling and modal vibration elastic analyses of ring stiffened, branched, segmented shells of revolution. Different loads can be applied simultaneously, i.e., loads that increase proportionally with each other, or combination of loads. Bosor4 has been used as a solver in structural optimisation software known as GENOPT. It is a part of a wider suite of software devoted to buckling of shell structures (elastic-plastic, creep) documented in Ref. [13]. Its implementation is based on finite differences, and Ref. [13] provides a comprehensive list of papers where detailed theory behind